

Radiation Damage and Single Event Effect Results for Candidate Spacecraft Electronics

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Abstract

We present data on the vulnerability of a variety of candidate spacecraft electronics to proton and heavy-ion induced single-event effects and proton-induced damage. We also present data on the susceptibility of parts to functional degradation resulting from total ionizing dose at low dose rates (0.003–4.52 rads(Si)/s). Devices tested include optoelectronics, digital, analog, linear bipolar, hybrid devices, Analog-to-Digital Converters (ADCs), Digital-to-Analog Converters (DACs), and DC-DC converters, among others.

I. INTRODUCTION

As spacecraft designers use increasing numbers of commercial and emerging technology devices to meet stringent performance, economic and schedule requirements, ground-based testing of such devices for susceptibility to single-event effects (SEE), Co-60 total ionizing dose (TID) and proton-induced damage has assumed ever greater importance. Recent experience in satellite design has also emphasized the increased susceptibility of bipolar devices to damage from TID at low dose rates (0.001–0.01 rads (Si)/s). The results discussed here include low-dose-rate (0.003–4.52 rads (Si)/s) testing of a variety of devices representing several different vendors and fabricated in many different technologies.

The studies discussed here were undertaken to establish the sensitivities of candidate spacecraft electronics to heavy-ion and proton-induced single-event upsets (SEU), single-event latchup (SEL), single event transient (SET), TID, and proton damage (ionizing and non-ionizing).

II. TEST TECHNIQUES AND SETUP

A. Test Facilities

All SEE and proton-induced damage tests were performed between February 1999 and February 2000. TID tests were performed between February 1998 and February 2000. TID testing was performed using Co⁶⁰ sources at the Goddard Space Flight Center Radiation Effects Facility (GSFC-REF) and at Johns Hopkins University Applied Physics Laboratory (APL). Heavy-Ion experiments were conducted at the Brookhaven National Laboratories Single-Event Upset Test Facility (SEUTF). The SEUTF uses a twin Tandem Van De Graaf accelerator that can provide ions and energies suitable for SEU testing. Test boards containing the device under test (DUT) were mounted within a vacuum chamber. The DUT was irradiated with ions with linear energy transfers (LETs) of 1.1 to 120 MeV•cm²mg⁻¹, with fluences from 1x10⁵ to 1x10⁷ particles•cm⁻². Fluxes ranged from 1x10² to 1x10⁵ particles•cm⁻² per second, depending on the device sensitivity. Representative ions used are listed in Table 1. LETs between the values listed were obtained by changing the angle of incidence of ion beam onto the DUT, thus changing the path length of the ion through the DUT. Energies and LETs available varied slightly from one test date to another.

Proton SEE and damage tests were performed at four facilities: the University of California Davis (UCD) Crocker Nuclear Laboratory (CNL), TRI-University Meson Facility (TRIUMF), and the Indiana University Cyclotron Facility (IUCF). Proton test energies incident on the DUT are listed in Table 2. Typically, the DUT was irradiated to a fluence from 1x10¹⁰ to 1x10¹¹ particles•cm⁻², with fluxes on the order of 1x10⁸ particles•cm⁻² per second.

Table 1: BNL Test Heavy Ions

Ion	Energy, MeV	LET in Si, MeV•cm ² /mg	Range in Si, μ m
C ¹²	102	1.4	193
F ¹⁹	141	3.4	126
Si ³⁵	186	7.9	85.3
Cl ³⁵	210	11.4	65.8
Ti ⁴⁸	227	18.8	47.5
Ni ⁵⁸	266	26.6	41.9
Br ⁷⁹	290	37.2	39
I ¹²⁷	320	59.7	34
Au ¹⁹⁷	350	82.3	27.9

Table 2: Proton Test Facilities

Facility	Particle	Particle Energy, (MeV)
University of California at Davis (UCD) Crocker Nuclear Laboratory	Proton	26.6-63
TRI-University Meson Facility (TRIUMF)	Proton	50-500
Indiana University Cyclotron Facility (IUCF)	Proton	54-197

B. Test Method

Unless otherwise noted, all tests were performed at room temperature and nominal power supply voltages.

1) SEE Testing

Depending on the DUT and the test objectives, one or more of three SEE test methods were used:

Dynamic – the DUT was exercised continually while being exposed to the beam. The errors were counted, generally by comparing DUT output to an unirradiated reference device or other expected output. In some cases, the effects of clock speed or device modes was investigated. Results of such tests should be applied with caution, because device modes and clock speed can affect SEE results.

Static – the DUT was loaded prior to irradiation; data was retrieved and errors were counted after irradiation.

Biased (SEL only) – the DUT was biased and clocked while I_{CC} (power consumption) was monitored for SEL or other destructive effects.

In SEE experiments, DUTs were monitored for soft errors, such as SEUs and for hard errors, such as SEL. Detailed descriptions of the types of errors observed are noted in the individual test results.

2) Proton Damage Testing

Proton damage tests were performed on biased devices with functionality and parametrics being measured either continually during irradiation or after step irradiations (for example, every 10 krad (Si)).

Displacement damage test guidelines are currently under development. Optocoupler characterization approaches used in this study are found in [1].

3) TID Testing

TID testing was performed using Co-60 sources at GSFC-REF and APL. The source at GSFC-REF is capable of delivering dose rates from 0.003-1.1 Rad(Si)/s, with dosimetry being performed by an ion chamber probe. All NASA GSFC TID testing was annealed for a minimum of 168 hours at room temperature. TID testing at APL was conducted at a dose rate of ~4 rad (Si)/s. All TID testing used method 1019.5 as a guide.

Pre-irradiation functional and parametric tests were performed on all controls and test devices. The parts were then irradiated in steps from 1 to 20 kRad(Si) and tested after each step for parametric degradation and functionality.

III. TEST RESULTS OVERVIEW

Abbreviations and conventions are listed in Table 3. Abbreviations for principal investigators are listed in Table 4. SEE test results are summarized in Table 5. Unless otherwise noted, all LET_{th}s are in (MeV•cm²/mg) and all cross sections are in cm²/device. Displacement damage test results are summarized in Table 6. GSFC TID test results are summarized in Table 7. APL TID test results are summarized in Table 8. This paper is a summary of results. Complete test reports are available online at <http://radhome.gsfc.nasa.gov> [2].

Table 3: Abbreviations and Conventions:

H = heavy ion test
P = proton test (SEE)
LET = linear energy transfer (MeV•cm ² /mg)
LET _{th} = linear energy transfer threshold (the minimum LET value for which a given effect is observed for a fluence of 1x10 ⁷ particles/cm ² – in MeV•cm ² /mg)
LETmax = highest tested LET
SEU = single event upset
SEL = single event latchup
SET = single event transient
DD = displacement damage
< = SEE observed at lowest tested LET
> = No SEE observed at highest tested LET
PD = proton damage (both ionizing and non-ionizing)
TID = total ionizing dose
σ = cross section (cm ² /device, unless specified as cm ² /bit)
σ_{SAT} = saturation cross section (cm ² /device, unless specified as cm ² /bit)
LDC = lot date code
CTR = current transfer ratio
DAC = digital to analog converter
ADC = analog to digital converter
PROM = programmable read only memory
DSP = digital signal processors
ECL = emitter coupled logic
LED = light emitting diode
VCSEL = vertical cavity surface emitting laser
TTL = transistor-to-transistor logic
JFET = junction field-effect transistor
DRAM = dynamic random access memory

SRAM = static random access memory
 MOSFET = metal oxide semiconductor field emitter
 PIN = positive-intrinsic-negative
 FPGA = field programmable gate array
 Op Amp = operational amplifier
 V_{pp} = volts peak to peak
 V_{OS} = offset voltage
 V_{rms} = root mean squared voltage
 I_{SS}, I_{DD}, I_{IL}, I_{IH}, I_{DOFF}, I_{SOFF} = input current
 R_{ON} or R_{DS(ON)} = on resistance
 V_{GS} = gate source voltage
 V_{DS} = drain source voltage
 GPS = global positioning system

Table 4: List of Principal Investigators

Principal Investigator (PI)	Abbreviation
Kenneth LaBel	KL
Robert Reed	RR
Jim Howard	JH
Paul Marshall	PM
Cheryl Marshall	CM

Table 5: Summary of SEE Test Results

Part Number	Function	Manufacturer	Particle: (Facility)P.I.	Testing Preformed	Summary of Results
Power Devices:					
TL7702B	Power Supervisor	Texas Instruments	H: (BNL)RR/JH P: (IUCF)KL	SEE and P: SEE	H: SEL LET _{th} > 73, SET LET _{th} ~ 5-7, s _{SAT} =5x10 ⁻⁵ , results application specific P: No SEUs, SETs observed
TL7705B	Power Supervisor	Texas Instruments	H: (BNL)RR P: (IUCF)KL	SEE and P: SEE	H: SEL LET _{th} > 73, SET LET _{th} ~ 2.7-3.3, s _{SAT} =1x10 ⁻⁴ , results application specific P: No SEUs, SETs observed
TL7770-5	Power Supervisor	Texas Instruments	H: (BNL)RR	SEE	H: SEL LET _{th} > 73, SET observed but not measured
TLC7705	Power Supervisor	Texas Instruments	H: (BNL)RR	SEE	H: SEL LET _{th} > 73, SET LET _{th} ~ <3.3, s _{SAT} =1.5 x10 ⁻⁴ , results application specific
ADC/DAC:					
MX7225UQ	8 bit DAC	Maxim	H: (BNL)RR	SEL	SEL LET _{th} > 90
AD571S	ADC	AD	H: (BNL)RR/JH	SEL	SEL LET _{th} > 60
LTC1419	ADC	Linear Tech	H: (BNL)RR/JH	SEL	SEL LET _{th} > 60
DAC08	DAC	AD	H: (BNL)JH	SEL/SEU	SEL LET _{th} > 60, maybe SEU's at LET=60 for some conditions (application specific)
Memories:					
R29793	PROM	Fairchild	H: (BNL)JH	SEE	SEL LET _{th} > 37.4, two types of SEUs were observed, SEU LET _{th} ~3, s _{SAT} =3x10 ⁻³
Digital Signal Processors:					
RH21020	DSP	Lockheed-Martin	P: (UCD)KL	P: SEE	s = 7.64x10 ⁻¹¹ at 63 MeV
TSC21020F	DSP	Temic Semiconductor	P: (UCD)KL	P: SEE	s = 9.9x10 ⁻¹³ at 63 MeV
Logic Devices:					
10502	ECL Multiple NOR Gate	Motorola	H: (BNL)JH	SEL/SEU	SEL LET _{th} > 60, SEUs with LET _{th} ~ 26 and s _{SAT} =~1x10 ⁻⁶
MC74LCX08	2 Input and Gate	Motorola	H: (BNL)RR/JH	SEL	SEL LET _{th} > 60
Fiber Optic Links:					
HFBR-53D5	Transceiver	HP	P: (UCD)PM	P: SEE	Proton induced SETs observed. No destructive conditions observed to ~25 krad(Si) of 63 MeV protons
TTC-155M4	Transceiver	Lasermate	P: (UCD)PM	P: SEE	Proton induced SETs observed. No destructive conditions observed to ~25 krad(Si) of 63 MeV protons
TTC-155M2	Transceiver	Lasermate	P: (UCD)PM	P: SEE	Proton induced SETs observed. No destructive conditions observed to ~25 krad(Si) of 63 MeV protons

Table 5: Summary of SEE Test Results (Cont.)

Part Number	Function	Manufacturer	Particle: (Facility)P.I.	Testing Preformed	Summary of Results
Linear Bipolar Devices:					
CLC449	OP AMP	National Semiconductor	H: (BNL)RR	SET, SEL	SEL, SET LET _{th} > 60; SET result is application specific
PA07	High Power OP AMP	APEX	H: (BNL)RR	SET, SEL	SEL and SET are application specific. SEL, SET to LET _{th} > 37
LMC6081	Precision OP AMP	National Semiconductor	H: (BNL)JH	SEL	SEL LET _{th} > 60
HS139	Comparator	Harris	H: (BNL)JH	SET, SEL	SETs observed, SEL LET _{th} > 37
LM139	Comparator	National Semiconductor	H: (BNL)JH	SET, SEL	SETs observed, SEL LET _{th} > 59.8
MAX962	Comparator	Analog Devices	H: (BNL)JH	SEL	SEL LET _{th} > 60
AD783SQ	Sample and Hold Amplifier	Analog Devices	H: (BNL)RR	SET, SEL	SEL LET _{th} > 90, SET LET _{th} ~ 7, s _{SAT} =1x10 ⁻⁴
A250	Charge Sensitive Amp	Amptek	H: (BNL)RR	SET, SEL	SEL, SET LET _{th} > 60; SET is application specific
MSA0670	MMIC Amplifier	HP	H: (BNL)JH	SET, SEL	SEL, SET LET _{th} > 85
Optocouplers:					
OLH5601	Optocoupler	Isolink	P: (TRIUMF)RR	SET	Proton induced transients were observed, no significant parametric degradation
6N134	Optocoupler	Micropac	P: (TRIUMF)RR	SET	Proton induced transients were observed, no significant parametric degradation
Others:					
DS1670E	System Controller	Dallas Semiconductor	H: (BNL)RR	SEL	SEL LET _{th} ~ 15
SN54LVTH16244A	Buffer/Drivers	Texas Instruments	H: (BNL)RR/JH	SEL	SEL LET _{th} > 60
CGS74LCT2524	Clock Driver	National Semiconductor	H: (BNL)RR/JH	SEL	SEL LET _{th} > 60
MIC4423	MOSFET driver	Micrel	H: (BNL)RR	SET, SEL	SEL, SET LET _{th} > 60; SEL and SET are application specific
MC74HC4538A	Multivibrator	Motorola	H: (BNL)RR/JH	SEL	SEL LET _{th} > 60
DS1803	Dual Digital Potentiometer	Dallas Semiconductor	H: (BNL)RR	SEL, SEU	LET _{th} >20; SEL observed at LET <37

Table 6: Summary of Displacement Damage Test Results

Part Number	Function	Manufacturer	Particle: (Facility)P.I.	Testing Preformed	Summary of Results
Linears Bipolar Devices:					
LM111	Comparator	National Semiconductor	P: (UCD)JH (IUCF)JH	DD	Enhanced damage observed for Protons vs Co-60
Optocouplers:					
OLH249	Optocoupler	Isolink	P: (UCD)KL	DD	CTR degradation observed. See [1]
66099	Optocoupler	Micropac	P: (UCD)RR	P: DD	CTR measurements for 63 MeV; V _{ce} =5V
Optoelectronics:					
OD800	LED	Optodiode	P: (UCD)RR/PM	DD	60% light output degradation at 2.7x10 ¹⁰
HFE-4080	VCSEL	Honeywell	P: (UCD)CM	TID, DD	Only minimal changes in the threshold currents were observed for fluences up to 5x10 ¹³ cm ⁻² for 63 MeV protons

Table 7: Summary of NASA GSFC TID Test Results

Manufacturer & Part Number.	Part Type	LDC	Test Level (krads)(Si)	Effective Dose Rate (rads)/s(Si)	Param. Degrad. Level (krads)(Si)	Radiation Sensitive Parameters	Report Number	Comments
Comparators:								
Maxim MX913	TTL Comparator	9704	100	0.0035-0.174	>100	None	PPM-98-018	
AD CMP01 (V _{CC} =5 V)	Voltage Comparator	9729	200	0.33	>200	None	PPM-98-015	
AD CMP01 (V _{CC} =15 V)	Voltage Comparator	9729	200	0.33	>60	I _b , CMRR, I _{os}	PPM-98-015	Improved after 240 hr @ 25°C anneal
AD PM139	Comparator	9720A	200	0.33	>200	None	PPM-98-010	
FPGA:								
Actel A1280A	FPGA	Not marked	3-15	0.01	>5	Increase in supply current	PPM-98-032	Improved after 168 hr @ 25°C anneal
Operational Amplifiers:								
NSC LMC6464	CMOS Op Amp	9722	5.0, 10.0	0.03	N/A	Multiple parameters	PPM-99-041	Catastrophic failure at 5-10 krads(Si)
NSC (Comlinear) CLC502	Op Amp	Not marked	5-100	0.035-0.174	100	N/A	PPM-98-018	
AD AD783SQ	Sample & Hold Amp.	9702	2.5-50	0.04	N/A	N/A	PPM-99-040	Passed all tests to 50 krads(Si)
AD AD620	Inst. Op Amp	9815	5.0-25	0.04	5-10	Bias currents	PPM-99-029	
AD AD845	CBFET Op Amp	9846	2.5-50	0.04	>20	Multiple parameters	PPM-99-026	
AD OP-07	Op Amp	9723B	10-40	0.14	>10	Offset voltage	PPM-99-017	Some recovery after anneal
AD OP-07	Op Amp	9724A	5-40	0.14	~20	Offset voltage	PPM-99-016	Some recovery after anneal
AD OP-07	Op Amp	9724	20-200	0.14 and 0.58	~20	Multiple parameters	PPM-99-001	Degradation worse for higher rate. Lot had outliers in Vos
AD OP-07	Op Amp	9723B	20-200	0.33	~20	Offset voltage, then multiple parameters	PPM-98-011	Lot had outliers in Vos.
AD AMP01	Inst. Amp.	9818A	2.5-50	0.02	>5	Offset voltages, gain errors	PPM-99-015	
AD OP467	Op. Amp.	9812A	2.5-50	0.04	>10	Bias currents	PPM-99-004	
AD OP400	Op. Amp	9814A	2.5-50	0.04	>5	Bias currents, slew rate, gain	PPM-99-003	
AD OP270	Op. Amp.	9815	2.5-50	0.04	>5	Bias currents	PPM-98-029	
AD OP27	Op. Amp.	9721A	20-200	0.333	<20-40	Offset voltages	PPM-98-009	
AD OP15	Op. Amp.	9722A	20-200	0.333	20-40	Offset voltage, leakage currents	PPM-98-008	
AD AD585	Sample & Hold Amp.	9648	5-100	0.035-0.174	>30	Common-mode rejection ratio, offset voltage	PPM-98-006	
AD AD524	Inst. Amp.	9650A	5-100	0.072	>20	Offset voltages	PPM-98-005	
LT LF155A	Op. Amp. JFET input	9811	2.5-30	0.04	>10	Bias currents	PPM-99-035	
LT LT1010	Pwr. Buffer	9808	2.5-100	0.08	>100	N/A	PPM-99-010	
LT LF198	Sample & Hold Amp.	9129	20-200	0.33	>200	N/A	PPM-99-009	
LT LF147	Op. Amp.	9803	2.0-10 (low-dose rate) 2.5-50	0.004 0.02	See * in comments section	Multiple parameters	PPM-99-002	Low-rate tests, no significant degradation to 10krads(Si) * High rate: 5 krads showed sig. Degradation; not seen at lower rate
Burr- Brown INA117SM	Diff. Amp.	9837	10-50	0.06	>17.5	Offset voltage	PPM-99-033	
Apex PA07M	Power Op. Amp.	9918	10-50	0.06	>17.5	Offset voltage	PPM-99-032	
Amptek A250	Preamplifier	9902	10-100	0.07	>100	N/A	PPM-99-031	
Maxim MAX494	Op. Amp.	9639	5-100	0.06	>10	Bias currents	PPM-98-019	
Omnirel OM11725SMX	Op. Amp.	9735	5-75	0.043	>20	Line voltages	PPM-98-002	Note: catastrophic functional failure 15-75 krads(Si)

Table 7: Summary of NASA GSFC TID Test Results (Cont.)

Manufacturer & Part Number.	Part Type	LDC	Test Level (krads)(Si)	Effective Dose Rate (rads)/s(Si)	Param. Degrad. Level (krads)(Si)	Radiation Sensitive Parameters	Report Number	Comments
Analog-to-Digital and Digital-to-Analog Converters:								
AD AD7821	8-Bit ADC	9727	2.5-50	0.04	>30	Missing codes, integral nonlinearity	PPM-99-045	
AD AD7885	16-Bit ADC	9827	2.5-50	0.06	>50	N/A	PPM-99-039	
AD AD571	10-Bit ADC	9746	20-200	0.33	>200	N/A	PPM-98-024	
AD AD976	16-Bit ADC (BiCMOS)	9723	5-100	0.033	<5	Missing codes, integral and differential nonlinearity	PPM-98-001	Note parts may exhibit low-dose-rate susceptibility
AD DAC08	8-Bit DAC	9831	10-50	0.05	>25	Power supply sensitivity	PPM-99-036	
AD AD7535	14-Bit DAC	9812	10-25	0.05	>10	Integral and differential nonlinearity	PPM-99-027	
AD AD7545	12-Bit DAC	9807	2.5-30	0.07	>5	Integral and differential nonlinearity; leakage currents	PPM-99-022	
AD AD8222	12-Bit DAC	9738	Group A: 2.5-5; Group B: 1-10	Group A: 0.004 Group B: 0.003	A: <2.5 B: <1	Multiple parameters	PPM-99-006	
Maxim MX7225	8-Bit DAC	9321	2.5-30	0.04	>10	Multiple parameters	PPM-99-042	
Maxim MX536	RMS-DC Converter	9817	2.5-100	0.06	>10	VOS, Vrms	PPM-99-008	
Micronetworks MN5295	16-bit DAC	9549 9540	5-35	0.019	>15	Missing codes, integral and diff. Nonlinearity	PPM-99-018	
Voltage Regulators and Voltage References:								
Linfinity PIC7527	Switching Regulator	9450	2.5-50	0.06	>50	N/A	PPM-99-038	
NSC LM117K	Voltage Regulator	9808	10-30	0.08	>10	Line voltages	PPM-99-034	
NSC LM117H	Voltage Regulator	9727	20-200	0.33	>20	Line voltages	PPM-98-026	No improvement after anneal
NSC LM117HVK	Voltage Regulator	9732	20-200	0.33	>/~20	Line voltages	PPM-98-021	
NSC LM117HVH	Voltage Regulator	9727	20-200	0.33	>20	Line voltages	PPM-98-020	
Omnirel OM3914	Neg. Voltage Reg.	9909	2.5-50	0.05	>10	Ref. Voltage, line reg.	PPM-99-028	
Omnirel OM1850STM3	Voltage Regulator	9912	2.5-50	0.04	>10	Ref. Voltage, line reg.	PPM-99-024	
AD AD588	Voltage Reference	9814	2.5-100	0.05	>15	Minor shifts in voltage levels	PPM-99-014	
AD AD780	Voltage Reference	9728	2.5-100	0.08	>100	N/A	PPM-99-011	
Memories:								
Samsung KM48C800AS-6U	8MBx8 DRAM	Multiple wafer lots	Batch1: 2.5-100 Batch2: 20-100	Batch 1: 0.09 Batch 2: 0.06	>20	Supply currents, functional	PPM-99-030	
Samsung KM684002AJ-17	512Kx8 SRAM	9826	2.5-100	0.05	>30	Leakage currents, functional failure	PPM-99-014	
SEEQ/ATMEL 28C256	256K EEPROM	9133	1-25	0.01	>20	Functional failure	PPM-98-023	
Fairchild/Raytheon R29773	2Kx8 PROM	9347	20-200	0.33	>200	N/A	PPM-98-013	

Table 7: Summary of NASA GSFC TID Test Results (Cont.)

Manufacturer & Part Number.	Part Type	LDC	Test Level (krads)(Si)	Effective Dose Rate (rads/s)(Si)	Param. Degrad. Level (krads)(Si)	Radiation Sensitive Parameters	Report Number	Comments
Analog Switches and Multiplexers:								
Maxim DG412	Analog Switch	9829	15	0.006	<2.5	I _{SS} , I _{DD} , I _{IL} , I _{IH} , I _{DOFF} , I _{SOFF}	PPM-99-012	Functional to >15 krads
Maxim DG403	Analog Switch	9810	5-10	0.02, 0.003	<2.5	I _{DD} , I _{SS} , I _{IH} , I _{IL} and R _{ON}	PPM-99-007	Failed functionality at 7.5-20 krads
Harris HI300	Analog Switch	9816	5-50	0.03	<2.5	I _{IH} , I _{IL} , and (for >30 krad) I _{SS} , I _{DD} and R _{ON}	PPM-99-005	Parts annealed at 5.0 and 50 krad; functional despite parametric degradation
Harris HI506	Multiplexer	9745	50	0.04	>50	N/A	PPM-98-028	
Power Devices:								
Lambda/Advanced Analog ATR2815TF	DC-DC Converter	9907	5-25	0.022	>10	Efficiency, line reg	PPM-99-020	
Interpoint MTR2815	DC-DC Converter	9830	2.5-100	0.09	15-50	Input current	PPM-98-031	
Interpoint MTR2805	DC-DC Converter	9828	2.5-100	0.09	>50	Multiple parameters	PPM-98-030	
Linfinity SG1846	Pulse-Width Modulator	9715	20-200	0.33	>80	Error-amp section parameters	PPM-98-022	
Miscellaneous:								
NSC 54ABT245A	Transceiver	9736	10-50	0.05	17.5	Leakage currents	PPM-99-037	
Micrel MIC4424	Dual MOSFET Driver	9832	5-75	0.058	20	Functionality	PPM-99-019	
Q-Tech QT22AC10M	36 MHz Xtal Osc.	9842	5-100	0.08	>100	N/A	PPM-99-021	
National DS7830	Diff. Line Driver	9749	20-200	0.33	>200	N/A	PPM-98-025	
National 54AC74	Dual Flip-Flop	9610	5-100	0.16	>5	Power supply voltages	PPM-98-027	
Omnirel OM20P10	P-Channel MOSFET	9735	2.5-20	0.03	>10	Threshold VGS, VDS, RDSon	PPM-99-025	
Harris 2N7225	N-Channel MOSFET	9827	2.5-50	0.06	>10	Threshold VGS	PPM-99-023	
Solitron 2N5115	PJFET	9430	5-100	0.089	5-15	Leakage currents	PPM-98-004	One failure after 5 krads
Motorola 2N4858	NJFET	9333	5-100	0.072	>100	N/A	PPM-98-003	

Table 8: Summary of NASA TID Test Results from APL

Manufacturer & Part Number	Part Type	LDC	Test Level (krads) (Si)	Effective Dose Rate (rads/s)(Si)	Para. Degrad. Level (krads)(Si)	Radiation Sensitive Parameters	Report Number	Comments
Comparators								
Maxim MAX962ESA	Dual Comparator	9627	5 - 30	4.52	> 30	None	SOR-5-00005	
Maxim MAX972ESA	Open Drain Comparator	9821	5	4.52	< 5	I ₊ , VOS	SOR-5-99010	All functionally failed at 5 krads with no recovery after anneal.
Operational Amplifiers								
NSC LMC6081AIM	Precision Op Amp	9824	5 - 10	4.52	> 4	VOS, ISC, AV1±, AV2±	SOR-5-99014	
Voltage Regulators and Voltage References								
NSC LP2952IM	Voltage Regulator	9830	5 - 15	4.52	> 5	IGND2, IGND3	SOR-5-00003	Out of spec at 5 krads but in spec at 15 krads anneal.
Linear Tech. LT1580 IR-2.5	2.5 V Voltage Regulator	9813	5 - 30	4.52	> 22	Output Voltage	SOR-5-99031	Out of spec at 22 krads but in spec at 30 krads anneal.

Table 8: Summary of NASA TID Test Results from APL (Cont.)

Memories								
AMD AM29LV800Bx1 20EE	Flash Memory	9735	6 – 8	4.52	> 6	Functionality	SOR-5-99015	Failure at 8 krad. Recovered after 168 hr 100°C anneal.
Micron MT48LC1M16A1 TG-10SIT	100MHz SDRAM, 1Mx16	9844	5 - 30	4.52	> 30	None	SOR-5-99017	
Power Devices								
IR IRLR2905	Power N- MOSFET	9827	5 – 20	4.52	> 7.5	IDSS, BV	SOR-5-99030	Out of spec at 7.5 krad but in spec at 20 krad anneal.
Microprocessors, Controllers, and Gate Arrays								
Dallas Semiconductor DS1670E	Portable System Controller	9744	5 - 30	4.52	> 30	None	SOR-5-99023	
Lucent Tech. OR2T15A2S240 DB	FPGA	9833	5 - 30	4.52	> 25	ICCH, ICCL	SOR-5-99029	Out of spec at 25 krad but in spec at 30 krad anneal.
Miscellaneous								
NSC CGS74LCT252 M	Clock Driver	9824	5 - 30	4.52	> 30	None	SOR-5-99013	
Dallas Semiconductor DS1803Z-010	Dual, Addressable Potentiometer	9834	5 - 30	4.52	> 30	ISB	SOR-5-99028	Out of spec at 30 krad but recovered after 100°C anneal.
Linear Tech. LTC1153CS8	Electronic Circuit Breaker	9745	5 – 15	4.52	< 5	Vgate1, Vgate2, IQon2, IQoff	SOR-5-99009	One of five failed at 5 krad. All 5 failed by 15 krad.
Linear Tech. LTC1157CS8	3.3V MOSFET Driver	9625	5 – 10	4.52	> 5	VO1, VO2, VO3, IQ11	SOR-5-00004	All failed functionally at 15 krad with no recovery after anneal.
Motorola MC74HC4538A D	Monostable Multivib.	9745	5 - 30	4.52	> 30	None	SOR-5-99011	
Motorola MC74LCX08D	2-Input NAND	9834	5 - 30	4.52	> 30	None	SOR-5-99012	
Texas Instruments SN74LVT16244	Line Drvr/Buffer	9618	5 - 30	4.52	>15	ICC, ICCZ, IOZL1	SOR-5-99027	Out of spec at 15 krad but in spec at 30 krad anneal.
Synergy SY100EL16VZC	5/3.3V Diff. Receiver	9838L	5 - 30	4.52	> 30	None	SOR-5-99018	
Synergy SY100EL31ZC	D-Flip Flop	9822A	5 - 30	4.52	> 30	None	SOR-5-99019	
Synergy SY10EL15ZC	1:4 Clock Distrib.	9703	5 - 30	4.52	> 30	None	SOR-5-99020	

IV. SEE TEST RESULTS AND DISCUSSION

A. Power Devices

1) TL7702B, TLC7705, TL7705B and TL7770-5 Heavy Ion Testing

Test for radiation-induced SET and SEL susceptibility of the Texas Instruments TL7702B, TLC7705, TL7705B and TL7770-5 power-supply supervisors were performed at the BNL SEUTF. Output of the device was monitored for radiation induced errors. (Only undervoltage conditions were tested for the TL7770-5). The power supply current was

monitored for large current increase and the device functionality was monitored.

None of the devices experienced SELs for the test conditions and circuit configurations used, (see the test synopsis [3, 4] for details of testing conditions). All were exposed to a maximum LET of 70 MeV•cm²/mg.

For the TL7770-5, high to low SETs were observed at LETs between 37 and 70 MeV•cm²/mg (lower LETs were not tested). However, the SETs were too short in duration (<2μs) to be captured by the automated data collection system. SET pulse heights varied from just visible on the digital

oscilloscope to dropouts that went all the way to ground. No low to high SETs were observed.

SETs were observed while exposing the TCL7705, TL7705B and TL7702B to heavy ions. These tests were application specific. Details of the test techniques can be found in the test synopsis [3]. We visually observed that the SETs were typically 25ms in duration, with magnitudes all the way to ground. The LET_{th} of the TCL7705, was measured to be less than $3.3 \text{ MeV}\cdot\text{cm}^2/\text{mg}$. The LET_{th} was between 2.7 and $3.3 \text{ MeV}\cdot\text{cm}^2/\text{mg}$ for the TL7705B and between 5 and 7 for the TL7702B.

2) TL7702B and TL7705B Proton Testing

Proton induced SEE testing on Texas Instruments power supervisors TL7702B and TL7705B was performed at IUCF.

No errors, anomalies, or destructive conditions were observed on 2 test samples of the TL7702B to a cumulative fluence of $6.56 \times 10^{11} \text{ protons}/\text{cm}^2$ (40 krad (Si) of TID). Thus, the limiting device cross-section is $1.52 \times 10^{-12} \text{ cm}^2/\text{device}$. No obvious degradation due to TID or displacement damage was observed.

No errors, anomalies, or destructive conditions were observed on 2 test samples of the TL7705B to a cumulative fluence of $6.56 \times 10^{11} \text{ protons}/\text{cm}^2$ (40 krad (Si) of TID). Thus, the limiting device cross-section is $1.52 \times 10^{-12} \text{ cm}^2/\text{device}$. No obvious degradation due to TID or displacement damage was observed. Transient output spikes were not investigated during testing.

B. ADC/DAC

1) Maxim MX7225 8-bit DAC

Testing was performed at BNL to determine the SEL susceptibility of the Maxim MX7225 as a function of supply voltage and ion LET.

The MX7225 did not experience any SELs for the test conditions investigated. Details of the test setup can be found in [5]. Thus, for SEL the DUT has an $LET_{th} > 84.7 \text{ MeV}\cdot\text{cm}^2/\text{mg}$ with a limiting cross-section $< 1 \times 10^{-7} \text{ cm}^2$.

2) Analog Devices AD571S ADC

The device was monitored for SEL while exposing it to a number of heavy-ion beams at BNL. Supply current was monitored for an increase or decrease. No SELs were observed for the AD571S analog-to-digital converter up to LET of $60 \text{ MeV}\cdot\text{cm}^2/\text{mg}$.

3) Linear Technologies LTC1419 ADC

The Linear Technologies LTC1419 was monitored for SEL while exposing it to a number of heavy-ion beams at BNL [6]. Supply current was monitored for an increase or decrease.

No SELs were observed up to LET of $119.6 \text{ MeV}\cdot\text{cm}^2/\text{mg}$ on 3 devices tested under bias conditions of 7 volts at all ion LETs to a fluence of $1 \times 10^7 \text{ p}/\text{cm}^2$.

4) Analog Devices DAC08 DAC

The Analog Devices (AD) DAC08 digital-to-analog converter was tested at BNL to determine its SET and SEL sensitivity as a function of input code (output voltage) and

particle LET. The DAC was operated in a dc mode as required for the application for which the test was conducted (dc output mode only).

The devices were exposed to a fluence of $10^7 \text{ particles}/\text{cm}^2$ of Ti^{46} , Br^{79} and I^{127} ions with no single event upsets or latchup being observed. An occasional trigger on the digital scope was noted, indicating a possible event. Upon review of the data, it was determined that these events were just noise. The upset window was kept small intentionally to catch upsets of even the LSB, so temporary fluctuations of noise could trigger the scope. The events observed were very infrequent (approximately 15 events in 2×10^8 ions) and did not have a detrimental impact on the testing. The Analog Devices (AD) DAC08 digital-to-analog Converter is considered to have an LET_{th} for upsets and latchup greater than $119.6 \text{ MeV}\cdot\text{cm}^2/\text{mg}$. This SEL result is valid for generic use, but since this testing was conducted for dc output mode only, the SEU portion of this testing is application specific to operation in the dc output mode [7].

C. Fairchild R29793 Programmable Read Only Memory (PROM)

This R29793 device was tested while operating at a frequency of 1 MHz for the nominal supply voltage ($V_s = 5$ Volts) with a checkerboard pattern (55AA).

The devices were exposed to fluences from 5×10^5 to $1 \times 10^7 \text{ particles}/\text{cm}^2$ of Br^{79} and various fluences of the C^{12} , Si^{35} , and Cl^{35} ions (up to a fluence of 1×10^7 for the C^{12} ion) with no single event latchups. The Fairchild R29793 PROM is likely to have an LET_{th} for latchup greater than $37.4 \text{ MeV}\cdot\text{cm}^2/\text{mg}$.

SEUs, on the other hand, were common. During the testing, it became apparent that there were actually two modes of upsets. These were single cell upsets and massive-device-failure upsets (where approximately all storage locations would read incorrectly). For the single cell upsets, the approximate LET_{th} is $3 \text{ MeV}\cdot\text{cm}^2/\text{mg}$ and the device saturation cross section is $3 \times 10^{-3} \text{ cm}^2$. For the massive-error events, the approximate LET_{th} is $5 \text{ MeV}\cdot\text{cm}^2/\text{mg}$ and the device saturation cross section is $1 \times 10^{-4} \text{ cm}^2$.

For the massive-error events, the ion beam flux was allowed to continue until the error counter jumped, nearly instantaneously, to more than 70,000 errors. On occasion, before the beam could be stopped, a second massive-error event was observed with the counter jumping to more than 140,000. From Figure 1, it can be seen that for both normally and obliquely incident C^{12} ion beams, no massive-error events were observed. At the higher LETs of 7.88 and $11.4 \text{ MeV}\cdot\text{cm}^2/\text{mg}$, all the devices experienced these errors at highly variable rates [8].

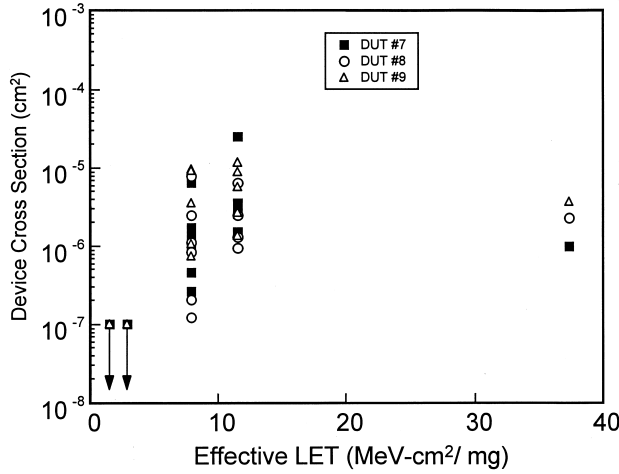


Fig. 1. Fairchild R29793 device cross section as a function of effective LET for the massive error events. Data points with a down-pointing arrow indicate that no events were observed under those conditions.

D. Digital Signal Processors

1) Lockheed-Martin RH21020

Lockheed-Martin RH21020s were tested for SEU and SEL under irradiation by proton beams in both dynamic and static modes. Outputs from the DUT were compared to those from an identical, non-irradiated reference chip and logged as errors when the outputs did not match. The DUTs were operated at 15 MHz (50% derated) and a power supply voltage of 5 volts. They were irradiated with proton fluences up to 1.4×10^{12} particles per cm^2 at fluxes ranging from 8.6×10^7 – 1.7×10^9 particles/ cm^2 per second. The total upset cross section of the DSP for protons was measured to be $7.93 \times 10^{-11} \text{ cm}^2$ per device. The total device cross section broke down as $5.64 \times 10^{-11} \text{ cm}^2$ per device for the Data Address Generator registers (DAG) and $2.29 \times 10^{-11} \text{ cm}^2$ for the General Purpose Registers (GPS). No upsets were observed for the Multiplier Registers, System Registers, Interrupt Registers or I/O portions of the device, implying a proton upset cross section less than $7.14 \times 10^{-13} \text{ cm}^2$ per device for these portions of the chip. Table 9 below summarizes the SEE test results for both the Lockheed-Martin RH21020 and the Temic Semiconductor TSC21020F. No latchup events were observed, consistent with heavy-ion-upset and -latchup test results reported previously [9].

2) Temic Semiconductor TSC21020F

Temic Semiconductor TSC21020Fs were tested for SEU and SEL under irradiation by proton beams in both dynamic and static modes. The devices were irradiated with proton fluences up to 1.4×10^{12} particles per cm^2 at fluxes ranging from 8.6×10^7 – 1.7×10^9 particles/ cm^2 per second. The total upset cross section of the DSP for protons was measured to be $9.9 \times 10^{-13} \text{ cm}^2$ per device. The cross section for the I/O is $9.9 \times 10^{-13} \text{ cm}^2$ per device. No upsets were observed for the Data Address Generator registers, Multiplier Registers, System Registers, or Interrupt Registers portions of the device,

implying a proton upset cross section less than $9.9 \times 10^{-13} \text{ cm}^2$ per device for these portions of the chip.

Table 9 below summarizes the SEE test results for both the Lockheed-Martin RH21020 and the Temic Semiconductor TSC21020F. All errors observed on both device types were data errors only. No errors requiring reset pulses were observed to the maximum test fluences.

Table 9: Proton SEE RH21020 and TSC21020F Area Test Results

Type of Error	Cross-section in $\text{cm}^2/\text{device}$ LMFS RH21020	Cross-section in $\text{cm}^2/\text{device}$ Temic TSC21020F
Overall DUT Data Address Generator	7.93×10^{-11}	9.90×10^{-13}
(DAG) Registers	5.64×10^{-11}	$4.95 \times 10^{-13*}$
General Purpose Registers (GPS)	2.29×10^{-11}	$4.95 \times 10^{-13*}$
Multiplier Registers	$7.14 \times 10^{-13*}$	$4.95 \times 10^{-13*}$
System Registers	$7.14 \times 10^{-13*}$	$4.95 \times 10^{-13*}$
Interrupt Registers	$7.14 \times 10^{-13*}$	$4.95 \times 10^{-13*}$
I/O errors	$7.14 \times 10^{-13*}$	9.90×10^{-13}

* indicates limiting cross-sections measured: no upsets observed in these areas of the device to the maximum test fluence

E. Logic Devices

1) Motorola 10502 ECL Multiple NOR Gate

The Motorola 10502 ECL Multiple NOR Gate was screened for SEU and SEL susceptibility as a function of particle LET. Test conditions included the nominal and worst-case supply voltage ($V_s = -5.2$ and -7 Volts). One input to the NOR gate was maintained at ground potential while the other was clocked at 100 kHz (as required by the HST application). A fluence of at least 1×10^7 ions/ cm^2 was used for each test condition. The beam flux range of 2.5×10^4 to 1.1×10^5 particles/ cm^2/s , resulted in individual exposures of between 1.6 and 6.7 minutes.

The effects of input voltage conditions were evaluated at 7 different LET values. Testing began with a normally incident I^{127} ions (LET=59.8) followed by normally incident Br^{79} and Ni^{58} ions (LET=37.3 and 26.6 $\text{MeV} \cdot \text{cm}^2/\text{mg}$ respectively). Angle of incidence was varied to obtain the rest of the seven effective LETs used. Four samples from the same lot and date code were tested under overlapping sets of conditions.

From Figure 2, it can be seen that for most LET conditions, the cross section data is fairly constant, but this is likely due to the statistical variations. At the lower LET values between 20 and 40 $\text{MeV} \cdot \text{cm}^2/\text{mg}$, there are cases where no events were observed. For all cases with effective LET greater than 40 $\text{MeV} \cdot \text{cm}^2/\text{mg}$, upsets were seen.

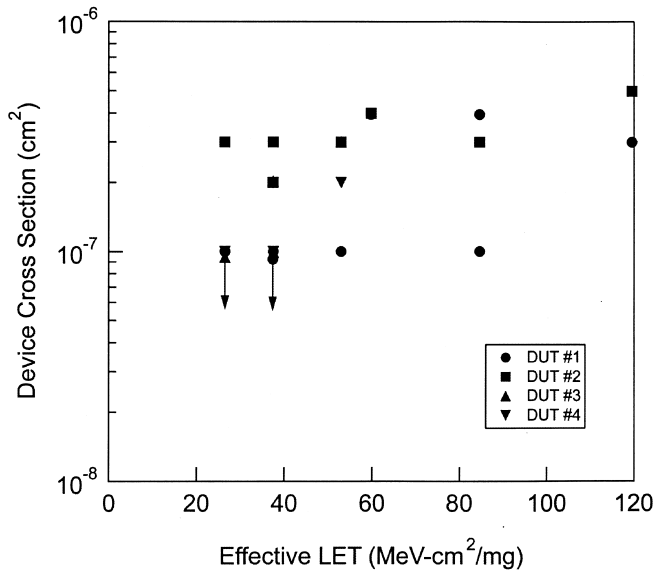


Fig. 2. Motorola 10502 Cross Section as a function of Effective LET. Data points with a down-pointing arrow indicate that no events were observed under those conditions.

The Motorola ECL Multiple NOR Gate is considered to have an LET_{th} for latchup greater than $119.6 \text{ MeV}\cdot\text{cm}^2/\text{mg}$ and the approximate LET_{th} for upset is $20 \text{ MeV}\cdot\text{cm}^2/\text{mg}$ with a device saturation cross section is $5 \times 10^{-7} \text{ cm}^2$. This latchup result is valid for generic use, but since this testing was done at a slow clock speed (100 kHz) and with one grounded input, the upset portion of this testing is application specific to this operational mode only [10].

2) Motorola MC74LCX08 2 Input and Gate

The device was monitored for SEL by exposing it to a number of heavy ion beams at BNL. Supply current was monitored for an increase or decrease. No SELs were observed for the MC74LCX08 up to LET of $60 \text{ MeV}\cdot\text{cm}^2/\text{mg}$.

F. Fiber Optic Links

1) HP HFBR-53D5 Transceiver

We conducted extensive proton SEE testing of the optical fiber-based HP HFBR-53D5 Gigabit Ethernet Transceiver with 850 nm VCSEL, Si p-i-n detector and a Si bipolar transimpedance amplifier (TIA). Throughout all tests the proton energy incident on the package was maintained at 63 MeV to ensure adequate penetration and knowledge of the proton energy at the circuit location. Test variables included proton angle of incidence, optical power incident on the receiver, data rate (up to 1100 Mbps), and part-to-part variation. Results indicated large transient cross-sections for the receiver. The transient characteristics and cross sections suggested the photodiode as the source. The cross-section increased approximately linearly with data rate and decreased with increasing incident optical powers (approximately a 10x decrease in cross section for a 10 dB increase in incident power). Significant cross section increases were noted for particles incident on the receiver photodiode at grazing angles. Under some test conditions, this increase exceeded two orders

of magnitude over the cross section seen at normal incidence. Little change was noted in device performance after an integrated 63 MeV proton fluence of over $3.8 \times 10^{12} \text{ cm}^{-2}$.

The test configuration had two transceivers on a card with an optical fiber cable connecting them and ECL in/out connectors to the BCP communications bit error rate tester (BERT). Using a pseudo-random sequence the bit-error cross sections were characterized as a function of optical power and data rate at various incident beam angles. The radiation susceptibilities of both the transmitter and receiver circuitry were monitored.

No catastrophic failures were observed to an exposure level of ~ 25 krad (Si) of 63 MeV protons. Figure 3 illustrates representative data captured during these experiments.

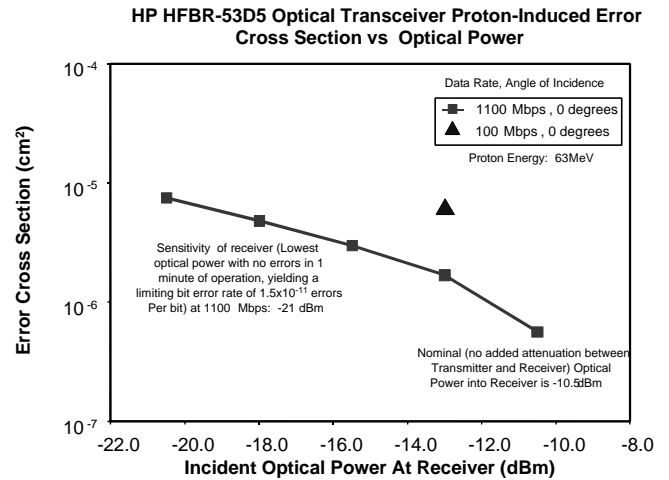


Fig. 3. Shows the effect of received optical power and data rate on radiation-induced error cross section for the HFBR-53D5 device.

2) Lasermate TTC-155M2 & TTC-155M4

We conducted extensive proton single event effects testing of the optical-fiber-based, 155 Mbps transceivers TTC-155M4 (850 nm VCSEL transmit/1300 nm receive) and TTC-155M2 (850 nm VCSEL transmit/850 nm Si PIN receive) fiber-optic-link hardware. Throughout all tests the proton energy incident on the package was maintained at 63 MeV to ensure adequate penetration and knowledge of the proton energy at the circuit location. Test variables included proton angle of incidence, optical power incident on the receiver, data rate (up to 1100 Mbps), and part-to-part variation. Results indicated large transient cross-sections for the receiver. The transient characteristics and cross-sections suggested the photodiode as the source. The cross-section increased approximately linearly with data rate and decreased with increasing optical powers (showing approximately 20x decrease for a 17dB increase in incident power). Significant increases in cross section were noted for beam angles at grazing incidence to the receiver photodiode. Under some test conditions, the increase exceeded two orders of magnitude compared to normal incidence. Negligible change in device performance was noted after an integrated 63 MeV proton fluence of over $4.8 \times 10^{11} \text{ cm}^{-2}$.

The test configuration had two transceivers on a card with an optical fiber cable connecting them and ECL in/out

connectors to the BCP communications bit error rate tester (BERT). Using a pseudo-random sequence the bit-error cross sections were characterized as a function of optical power and data rate for various incident beam angles. The radiation susceptibilities of both the transmitter and receiver circuitry were monitored.

No catastrophic failures were observed to an exposure level of ~25 krad (Si) at 63 MeV protons. Figure 4 illustrates representative data captured during these experiments.

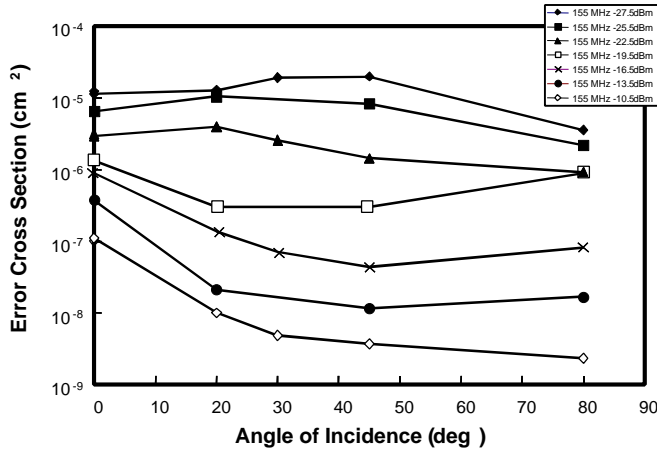


Fig. 4. Shows the measured effect of angular incidence and optical power on error cross section for the Lasermate TTC-155M4.

G. Linear Bipolar Devices

1) National Semiconductor CLC449 Ultra-Wideband Monolithic Op Amp

Tests were performed to screen for SEL and to measure SEL sensitivity as a function of supply voltage and particle LET. Test conditions included supply voltage (V_s) levels of $\pm 5V$ and $\pm 5.5V$. Supply currents were automatically monitored. The normally incident fluence was at least 9.5×10^6 ions/cm². The beam flux ranged from 1.2×10^4 to 1.0×10^5 particles/cm²/s, resulting in individual exposures between 95 and 790 seconds. The DUT was loaded with a 100 ohm resistor. For all cases, the input was 2 Volts peak-to-peak (V_{pp}) and the output was 4 V_{pp} . The typical input frequency was 200 MHz. The test setup limited the input frequency to 500 MHz.

Application specific SETs were observed. The CLC449 did not experience any SELs up to LET of 60 MeV•cm²/mg.

2) APEX PA07 High Power OP AMP

The APEX PA07 was monitored for SEL while exposing it to a number of heavy ion beams at BNL. Supply current was monitored for an increase or decrease. No SELs were observed up to LET of 60 MeV•cm²/mg.

3) National Semiconductor LMC6081 Precision OP AMP

The National Semiconductor LMC6081 was monitored for SEL while exposing it to a number of heavy ion beams at BNL. Supply current was monitored for an increase or decrease. No SELs were observed up to LET of 60 MeV•cm²/mg.

4) Harris HS139 and National Semiconductor LM139 Comparators

A study has been undertaken using linear comparators from two vendors (Harris, now Intersil, and National Semiconductor) to collect a sufficient amount of data under many operational conditions in an attempt to understand the SET generation and characteristics of these devices. This information is to be utilized in the development of a test methodology for comparators and possibly other linear devices.

Both LM139 and HS139 comparators produce SETs on their outputs. The cross sections and LET_{th}s for the comparators are only slightly sensitive to the applied bias. However, the LM139 cross section and LET_{th} has a strong dependence on the input differential voltage, first reported in [11]. The HS139 has an LET threshold of approximately 8-10 and a cross section of 3×10^{-4} cm². The LM139 has an LET threshold and cross section that vary with the input voltage differential from 1-10 (LET) and 1×10^{-5} to 3×10^{-4} cm² (cross section). It should also be noted that the output transient characteristics (peak height and pulse width) of the LM139 are also a strong function of input differential voltage.

5) National Semiconductor LM139 Comparator (Application Specific testing)

LM139 devices were exposed to a fluence of 1×10^6 to 1×10^7 particles/cm² of C¹², Ti⁴⁸, Ni⁵⁸, Br⁷⁹ and I¹²⁷ ions with no single event latchups. The National Semiconductor LM139 is considered to have an LET threshold for latchup greater than 59.8 MeV•cm²/mg. For single event transients, the approximate LET threshold for high output is 20 MeV•cm²/mg and the device saturation cross section is 2×10^{-4} cm². An approximate LET threshold of 20 MeV•cm²/mg and device saturation cross section of 1×10^{-4} cm² are seen for the low output conditions. It must be noted that these results are application specific [12]. Test conditions were: $V_{cc} = \pm 7$ volts and maintaining a volt differential between the input voltages: for $V_+ = 3$ Volts, V_- was set to 1 Volt, or vice versa.

6) Analog Devices MAX962 Comparator

The MAX962 was monitored for SEL while exposing it to a number of heavy ion beams at BNL. Supply current was monitored for an increase or decrease. No SELs were observed up to LET of 60 MeV•cm²/mg.

7) Analog Devices AD783SQ Sample and Hold Amplifier

The AD783 did not experience any SELs up to LET_{th} > 90 MeV•cm²/mg. Exposures were performed to a fluence of 1×10^7 p/cm² or greater. Figure 5 gives the results of application specific SET testing on the Analog Devices AD783. During testing we observed that the SETs were typically < 2 μ s in duration. The pulse height was typically somewhere between 0.4V and 1V. However we did observe some larger transients perhaps as large as 2-3V [13].

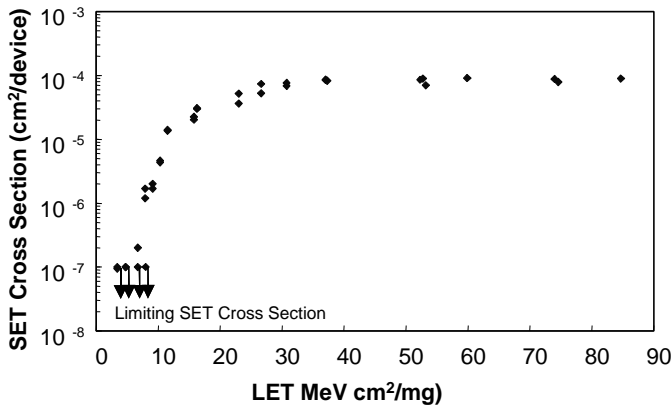


Fig. 5. Heavy ion SET cross section for AD783.

8) Amptek A250 Charge Sensitive Amplifier

The Amptek A250 was monitored for SEL while exposing it to a number of heavy ion beams at BNL. Supply current was monitored for an increase or decrease. No SELs were observed up to LET of 60 MeV·cm²/mg.

9) MSA-0670 MMIC Amplifier

The Hewlett Packard MSA-0670 MMIC was tested for susceptibility to SET and SEL under irradiation with heavy ions (265.9 MeV Ni⁵⁸ ions with LET=26.6 MeV·cm²/mg and 343 MeV I¹²⁷ ions with LET=59 MeV·cm²/mg). The device was tested for both nominal (7.93 volts) and worst-case (8.03 volts) supply voltages, and with $V_{in} = 0.5$ V @ 150 MHz. No SET or SEL events were seen for ion fluences of at least 1×10^7 particles/cm² at fluxes from 4.6×10^4 to 1.1×10^5 , with effective LETs up to 84.6 MeV·cm²/mg [14].

H. Optocouplers

1) Isolink OLS5601

Proton SET testing was performed at TRIUMF at proton energies of 68, 103, 160, and 225 MeV at CNL with 63 MeV protons. We observed SETs for various angles of incidence relative to the photodiode. The cross section increased with beam angle of incidence as it approached grazing angles to the photodiode for the 103, 63 and the 68 MeV beam. The angular effect was not observed for the higher energies.

2) Micropac 6N134

Proton SET testing was performed at TRIUMF at proton energies of 68, 103, 160, and 225 MeV. For all energies SETs were observed for all angles of incidence, with the cross section increasing as the beam angle approached grazing incidence to the photodiode.

I. Others

1) Dallas Semiconductor DS1670E System Controller

The DS1670E controllers experienced several SELs with several ions at several angles of incidence. The latchup current ranged from 40 to 109 mA. During the latchup condition the device was not functional, but the device recovered after a power cycle.

Figure 6 shows the device cross section for SEL at various LETs. The incident particle beam angle relative to the die was changed to obtain effective LETs between those listed in Table 1. The 3.3 V exposures are indicated by open circles,

and the 3.6 V exposures are shown as solid triangles. The data crossed by a solid horizontal line indicate that no events were observed during the exposure, i.e. limiting cross section [15].

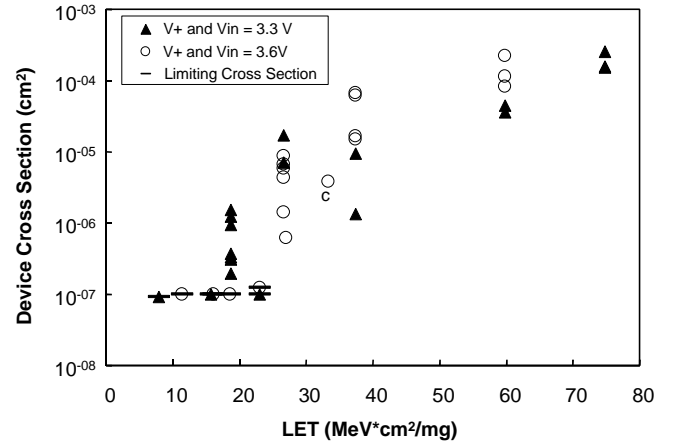


Fig. 6. Heavy Ion SEL cross section for DS1670E.

2) TI SN54LVTH16244A Buffer/ Drivers

Texas Instruments SN54LVTH16244A was monitored for SEL while exposing it to a number of heavy ion beams at BNL. Supply current was monitored for an increase or decrease. No SELs were observed up to LET of 60 MeV·cm²/mg.

3) National Semiconductor CGS74LCT2524 Clock Driver

The CGS74LCT2524 was monitored for SEL while exposing it to a number of heavy ion beams at BNL. Supply current was monitored for an increase or decrease. No SELs were observed up to LET of 60 MeV·cm²/mg.

4) Micrel MIC4423 MOSFET Driver

Tests were performed to screen for the possibility of SEL and to measure sensitivity as a function of input voltage, input frequency, case temperature, and particle LET. A normally incident fluence of at least 1×10^7 ions/cm² was used at each test condition. A beam flux of 8.2×10^5 to 1.4×10^5 particles/cm²/s resulted in individual exposures between 75 and 130 seconds. A 100 kHz signal was placed on the input oscillating between -5V and +12V. DC input signals of +12V and -5V were also used. For all cases the supply voltage (V_s) was 12V. The MIC4423 did not experience any SELs for the test conditions and circuit configuration described. Detailed test conditions for each exposure can be found in reference [16].

5) Motorola MC74HC4538A Multivibrator

The Motorola MC74HC4538A was monitored for SEL while exposing it to a number of heavy ion beams at BNL. Supply current was monitored for an increase or decrease. No SELs were observed up to LET of 60 MeV·cm²/mg.

6) Dallas Semiconductor DS1803 Addressable Dual Digital Potentiometer

Tests were performed on the DS1803 to screen for SEL and to measure SEL sensitivity as a function of supply voltage and particle LET. Test conditions included nominal and worst-case levels for the supply voltage (V_{cc}) of 3.3 V and 5.5 V. A normally incident fluence of at least 1×10^7 ions/cm² was

used at each test condition unless an SEL occurred. A beam flux range of 2×10^2 to 1.3×10^5 particles/cm²/s resulted in individual exposures between 10 second and 13 minutes. Both input voltage conditions (3.3 V and 5.5 V) were evaluated using 4 different ions and at several angles of beam incidence.

The device was monitored for high-current states and functionality by observing the resistance of the potentiometer. From time to time during the exposure, but before an SEL, the device was monitored to look for changes in the output as a crude look at the SEU susceptibility of the device. The number of SEUs was not recorded. Therefore the rate of occurrence in a space flight application can not be predicted.

The DS1803 experienced several SELs with several ions at several angles of incidence. The latchup current ranged from 51 to 57 mA. During the latchup condition the device was not functional, but the device recovered after a power cycle [17].

Figures 7 shows the device cross section for an SEL at various LETs. The 3.3 V exposures are indicated by open circles, and the 5.5 V exposures are denoted by the filled in triangles. The data crossed by a solid horizontal line indicate that no events were observed during the exposure. That is, these points represent limiting cross sections.

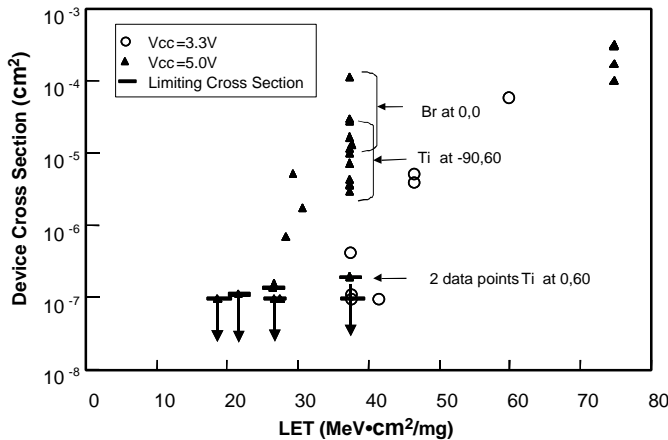


Fig. 7. DS1803 cross section for an SEL at various LETs

V. DISPLACEMENT DAMAGE TEST RESULTS AND DISCUSSION

A. National Semiconductor LM111 Comparator

It has been demonstrated that some linear devices are susceptible to enhanced degradation when exposed to proton environments as compared to Co-60. In an effort to understand this effect and develop an efficient test procedure, National Semiconductor Corporation (NSC) LM111 comparators have been exposed to proton environments at IUCF and UCD cyclotrons. The initial parameter investigated - and the most sensitive - is the input current. For consistency, this current was measured at what is termed the crossover point (one input is held at a voltage while the other is swept from the negative to positive side of that voltage. The crossover current is the point where the two input currents are equal).

To develop a complete data set for this investigation, rail voltages of ± 15 Volts, ± 10 Volts, ± 5 Volts and $\pm 15/0$ Volts were used. For all of these bias conditions, a crossover current was measured on six devices at input voltages from -3 to $+3$ Volts at 1 Volt increments. Examples of the data set are shown in figures 8 and 9. As can be seen, significant bias dependence is observed for both the rail bias and the input conditions.

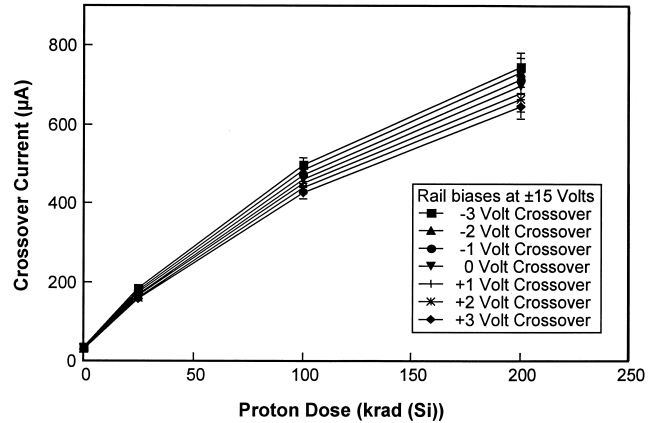


Fig. 8. Crossover currents of tested LM111 as a function of proton dose with a rail bias of ± 15 Volts. The data points are the average response of six parts and the error bars represent one sigma variation.

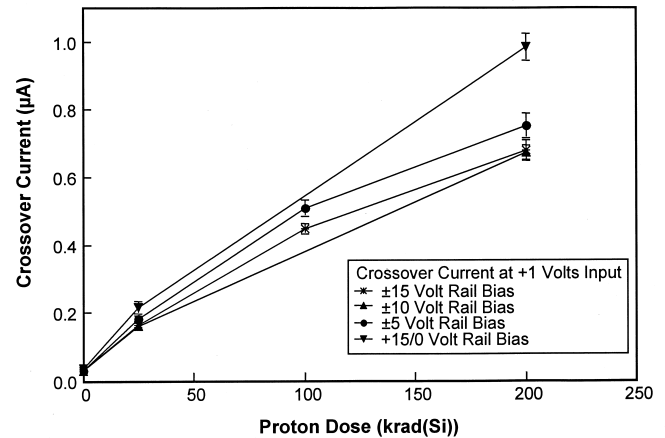


Fig. 9. Crossover currents of tested LM111 as a function of proton dose with crossover measured at $+1$ Volts at the inputs. The data points are the average response of six parts and the error bars represent one sigma variation.

B. Optocouplers

1) Isolink OLH249

The OLH249 was irradiated with 195 MeV protons at IUCF. The forward current I_F was swept from 4 to 26mA with $V_{CE} = 5V$. CTR degradation was observed at 6×10^{11} p/cm².

2) Micropac 66099

Proton effects characterization of the Micropac 66099 optocoupler were made at UCD using 63 MeV protons. Three devices (DUTs 1,2,3) were used for a quick set of measurements to ensure that reasonable choices were made for the proton fluences. A very detailed set of measurements was completed for an additional 3 devices (DUTS 4,5,6). The quick look was designed to be a worst-case look and was performed for a no-load condition with I_F at 1 mA and 5 mA.

The detailed measurements performed on a second set of 3 devices included CTR measurements for various loads (0, 430 Ω , 970 Ω , and 2.7 Ω) on the output and for I_F from 0.5 to 20 mA (in 0.5 mA increments) for each V_{CE} . V_{CE} itself was varied from 0 to 10 V in 1 V increments. Corresponding transistor measurements were also made. It is important to note that of the 6 devices tested, one exhibited anomalous post-irradiation behavior and performed significantly worse under irradiation. A detailed pre-irradiation characterization also revealed abnormalities in the device response under some conditions.

A range of initial CTRs was observed, and the spread in values depended on the operating conditions. Figure 10 shows a typical data set for the CTR as a function of proton fluence for various operating conditions. Note that the application with a 1k Ω load and I_F of 5mA has a significantly lower initial CTR but exhibits very little proton-induced degradation because the photo-transistor is in saturation [18].

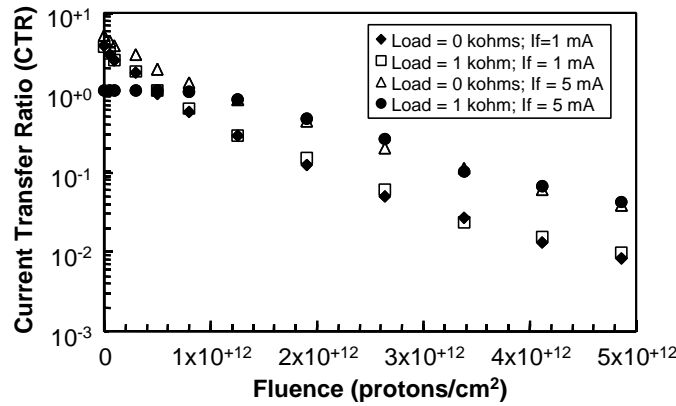


Fig. 10. CTR and transistor characteristics for the Micropac 66099.

C. Optodiode OD800 LED

Proton-induced degradation testing of the Optodiode OD800 light emitting diode was performed. LEDs were exposed to proton irradiations at UCD. The light output and I-V characteristics of the device were monitored for radiation-induced degradation at various fluence levels. The Optodiode OD800 is a GaAs Double Heterojunction light emitting diode. Figure 11 shows the degradation of the all the DUTs at each exposure level (fluence) for $I_F = 4$ mA. The measured output power (P) for each DUT at each fluence is normalized to the pre-irradiation output power (P_o). Figure 12 shows the I-V curves measured for DUT #18. The solid dark line indicates the pre-irradiation values, and the dashed line shows the post-irradiation values after an exposure 2.6×10^{11} p/cm². For the most part, the post- and pre-rad values are the same. In the configuration used, the current resolution of the parametric analyzer is thought to be ~ 1 nA. Measurements below 1 nA should be considered to have large error bars. The data presented in Figure 11 are consistent with results on DUTs 13-17, I-V curves were not measured for DUTs 1-12. See Reed et al., "Energy Dependence of Proton Damage in AlGaAs Light-Emitting Diodes" [19].

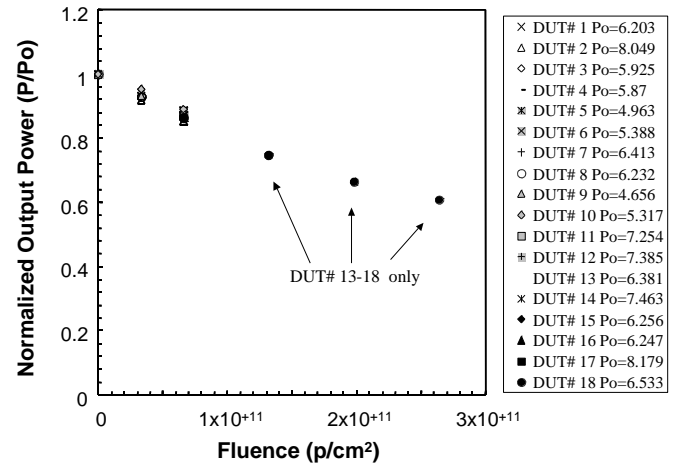


Fig. 11. Proton degradation of light output for 6 Optodiode OD800W. The output power was normalized to the pre-rad values.

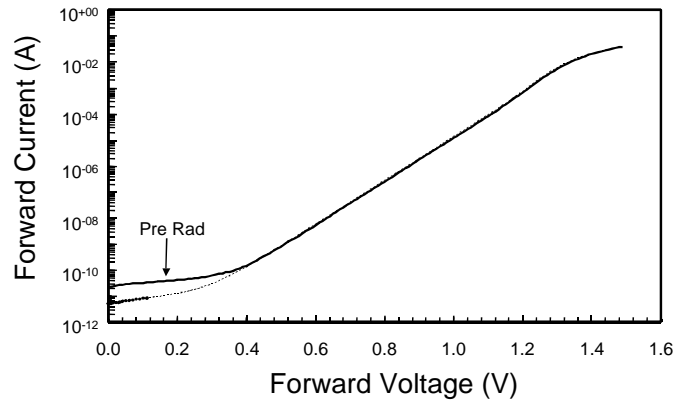


Fig. 12. Typical Optodiode OD800 DUT#18 post and pre-rad I-V curves.

D. Honeywell HFE-4080 a Vertical Cavity Surface Emitting Laser (VCSEL)

The Honeywell HFE-4080 ion-implanted 850 nm VCSELs were exposed unbiased to Co-60 gamma irradiation to ~ 1.8 Mrad(Si) to ensure that the Ultem lens in the package would not darken and obscure the proton test results. No significant gamma radiation-induced changes were observed.

Proton tests were performed at TRIUMF in May 1999, and at CNL in June 1999. The VCSELs were irradiated unbiased (which is a worst-case since there is no concurrent forward biased annealing). As expected the primary effect of proton exposure was an increase in the threshold drive current. For example, the threshold current increased from its initial value of ~ 5 mA to ~ 7 mA after a 63 MeV exposure of 5×10^{13} cm⁻². At the higher proton exposure levels, we also saw a decrease in the slopes of the light output versus drive current curves (i.e. the differential quantum efficiency).

Additional 850 nm oxide-confined VCSELs with different aperture sizes also underwent proton characterization. The smallest threshold current shifts were observed for the small-aperture, oxide-confined VCSELs. For example, the threshold current of the $4 \mu\text{m}^2$ oxide aperture VCSEL remained almost unchanged at ~ 0.5 mA after a 63 MeV fluence of 5×10^{13} cm⁻².

In summary, the VCSELs are very robust to gamma and proton irradiation and are suitable for most space applications.

VI. GSFC TID TEST RESULTS AND DISCUSSION

A. Comparators

TID evaluations were conducted for three different comparators, Maxim's MAX913 and Analog Devices' (AD) CMP01 and PM139, revealed varying susceptibility. In addition to functionality, parametric measurements of quantities such as power supply current (I_{CC}), input bias current (I_{ib}), offset voltage and current (V_{OS} and I_{OS}), common-mode rejection ratio (CMRR), power supply rejection ratio (PSRR) and gain (A_{oi}), were performed at each step during the irradiation and annealing processes.

B. Actel A1280A FPGA

Actel A1280A CQ172B FPGAs (5962-9215601MYC) were irradiated at a rate of 0.01 rad(Si)/s using a Co^{60} source. The parts were irradiated under bias to levels of 3.0, 5.0, 10.0 and 15.0 krad(Si). At levels above 5 krad(Si), supply currents were seen to increase above specified levels. Substantial improvement in these parameters was seen after a 168 hour anneal at 25°C.

C. Operational Amplifiers

The Radiation Effects and Analysis Group undertook 27 TID evaluations on 23 different amplifiers, 12 from Analog Devices (AD), 4 from Linear Technologies (LT), 2 from National Semiconductor (NSC) and one each from Burr Brown, Apex, Amptek, Maxim and Omnirel. Failure levels ranged from less than 5 krad(Si) to over 200 krad(Si). Functional and parametric tests were performed at every irradiation step.

D. Analog-to-Digital and Digital-to-Analog Converters

The Radiation Effects and Analysis Group undertook evaluations on 4 ADCs and 4 DACs from Analog Devices and on one DAC each from Maxim and Micronetworks. There was also one RMS-DC converter from Maxim. Parametric failure levels ranged from >200 krad(Si) to <1 krad(Si). For these devices, functional failures may be seen even before significant parametric degradation. At least one part (Analog Devices AD976) may exhibit ELDRS.

E. Voltage References and Voltage Regulators

Voltage references and regulators exhibit a wide range of susceptibilities to radiation damage. The 4 voltage regulators and 2 voltage references tested by the Radiation Effects Branch are consistent with this observation.

F. Memories

The speeds and capacities of commercial memories make them attractive to designers. They exhibit a broad range of radiation tolerances.

G. Analog Switches and Multiplexers

Parts were irradiated in steps from 2.5 krad to 5 krad. Prior to irradiation and after each step, tests were performed to measure supply currents, I_{DD} and I_{SS} , input leakage currents with inputs high and low, I_{IH} and I_{IL} , on-resistances, R_{ON} , and so on. The HI506 multiplexer showed no significant functional or parametric degradation for dose levels up to 50 krad(Si), as well as after a 168 hour, 25 °C anneal.

H. Power Devices

With the exception of the Linfinity PWM, the power devices tested were hybrid DC-DC converters, and they exhibit a range of radiation tolerances. The PWM exhibits good radiation tolerance.

I. Miscellaneous Devices

The devices in this category do not fit neatly into any of the other categories. They include discrete FETs, drivers, a crystal oscillator, a transceiver and a logic device. The failure levels are as diverse as the device types.

VII. APL TID TEST RESULTS AND DISCUSSION

A. Comparators

Two Maxim comparators were TID tested at the APL Co-60 test facility. While the MAX962ESA performed with no parametric shifts through the end dose value of 30 krad(Si), the MAX972ESA functionally failed at the first dose point of 5 krad(Si). All five tested parts that failed were annealed for 168 hours at 100 °C and showed no recovery.

B. Operational Amplifiers

Full parametric characterization of the National Semiconductor LMC6801AIM was conducted. The first parameters to fail in this test were gains, which fell below the specification limit at 4 krad(Si). At 5 krad(Si), offset voltage, supply current, input bias currents, and input offset currents failed. With all these parametric changes; the devices continued to function to 10krads (Si), when the parametric shifts were sufficiently large to terminate the test. Some, but not all, parameters recovered after anneal. The post-anneal results can be considered a measure of the "10 krad (Si) low-dose-rate performance".

C. Voltage References and Voltage Regulators

Two voltage regulators (NSC LP2952IM and Linear Tech LT1580 IR-2.5) were tested and each showed parametric shifts for the dose rate tested (4.52 rads/sec). Each part received a 168 hour 100 °C anneal and significant recovery was observed to expect low dose rate performances of 15 and 30 krad(Si), respectively.

D. Memories

An AMD Flash Memory and a Micron 1Mx16 SDRAM were TID characterized at the APL radiation facility. The Micron SDRAM experienced no parametric changes over the entire dose range tested (30 krad(Si)). The AMD flash memory, however, while functional at 6 krad(Si), failed

functionality testing at 8 krad (Si). Functionality at this dose level was restored after a 168 hour 100 °C anneal.

E. Power Devices

The international Rectifier IRLR2905 Power MOSFET was tested through 20 krad (Si) of TID. After approximately 7.5 krad (Si), I_{DSS} and Breakdown Voltage were out of specification. Both these parameters were back in specification, though, after 20 krad (Si) and a 168 hour 100 °C anneal.

F. Microprocessors, Controllers, and Gate Arrays

A Dallas Semiconductor DS1670E Portable System Controller and a Lucent Technology FPGA received full parametric TID screening at the APL Cobalt facility. Both parts performed very well with the DS1670E seeing no parametric shifts over the entire dose range of 30 krad (Si). The ORCA FPGA had two parameters out of specification at 25 krad (Si) but both were back in spec after 30 krad (Si) and a 168 hour 100 °C anneal.

G. Miscellaneous Devices

Ten other devices were tested at the Applied Physics Laboratory Co-60 test facility with functions that ranged from flip-flops to electronic circuit breakers. Of these, eight showed little or no parametric shifts through the full 30 krad (Si) range of testing. The two Linear Technology parts (LTC1153CS8 and LTC1157CS8) both began showing parametric shifts and functionality problems at approximately 5 krad (Si).

VIII. SUMMARY

We have presented recent data from SEE, Co-60 total ionizing dose (TID), and proton-induced damage on mostly commercial devices. It is the authors' recommendation that this data be used with caution. We also highly recommend that lot testing be performed on any suspect or commercial device.

IX. ACKNOWLEDGEMENTS

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